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6 An Assessment of the Use of Ceramics in Heat Engines.

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Ceramics Branch
Material Science and Technology Division

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This report presents the authors findings and conclusions from an assessment conducted for DARPA. The starting point for this assessment was the failure of the DARPA/Navy/Garrett Ceramic Turbine Program to meet the 50 hour engine demonstration goal. While this program produced many useful results, of particular pertinence to this assessment is that the rotating components appear to have been successful, but that this success and its extent were hidden by static component failure leading to complete engine failure.

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20 ABSTRACT (Continued)

The basic assessment of ceramics in heat engines is that extensive application is feasible and extremely important. But, it must be realized that it will have to be a large undertaking. The existance of foreign competition makes this a critical undertaking for the economic well being of the nation, as well as from a military capability standpoint. Feasibility is shown by the success of various components in the different demonstration programs which were often not totally successful because of the ambitious, complex nature of these programs. The importance of ceramics for heat engines is demonstrated by the impact of ceramic usage on consumption of both fuel and strategic metals, as well as by its potential impact on large industrial sectors in the United States and the serious economic competition with Europe and especially Japan. Both the Synfuels and very large scale integrated electronic programs are cited as useful references for economic perspective. It is suggested that ceramics in heat engines deserves and requires a national effort.

The immediate need from the Garrett program is to determine the extent of success of ceramic bladed metal rotors. This has potential practical payoff since in some applications ceramic blades may be used as the only ceramic components in a metal engine with over 50% of the benefit of using ceramics as both blades and vanes. However, since ceramic static hardware has an important contribution to make, solutions to the static hardware problems, much of which appears to be due to contact stresses between ceramic components, must be sought.

While major demonstration-programs have been, and continue to be, important the major need is for less glamorous "nuts and bolts" programs. The most critical longer range and broader of these needs is to develop manufacturing technology of existing ceramics, since this is the key to reliability, cost, as well as maintaining U.S. firms in the field. This is seen as a large undertaking requiring substantital investment. Part of this manufacturing effort should be coupled with design iteration efforts noted below. It is also clear that substantial funding must be made directly to the ceramic manufacturers involved.

Two other related needs lie in the material and design area. Broader development of a spectrum of advanced ceramics is needed to cover the spectrum of engine needs, including greater emphases on materials for piston engines. Evolution of existing materials, development of advanced materials, and seeking new materials are needed. Present work on carbon-carbon materials, which are seen as possible candidates, primarily for short life engines, is judged to be on an appropriate level at this time.

Design capability and versatility must be improved emphasizing specific problems in conventional design. This includes improving contact as well as thermal stress analysis. However, the most central need is design verification, i.e. including testing to failure, and subsequent design iteration. Consideration should also be given to trade-offs between ceramic coatings and monolithic ceramics, broader ranges of ceramic components, and combined cycles and systems. While novel designs, e.g. using blades in compression, could be useful, they need more basic level R&D investigation and more understanding of material behavior. Some of these programs require paritcular coordination and administration considerations. For example, the design iteration and manufacturing reliability efforts should be coupled and much of the materials devleopment work should be coupled with hardware/design test programs. Similarly, use of ceramic coatings on metal vanes with ceramic blades deserves serious consideration.

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FOREWORD

The views, conclusions, recommendations and opinions in this report are those of the author and do not necessarily reflect policy or attitudes of either the Navy or ARPA. The author wishes to acknowledge the extensive aid of many people, too numerous to cite, for their aid in preparing this report.

AN ASSESSMENT OF THE USE OF CERAMICS IN HEAT ENGINES

I. INTRODUCTION

A. Background

DARPA has funded major programs to demonstrate that ceramics can be successfully used in turbine engines, and hence greatly improve their performance. While the two primary programs, the Ford/Westinghouse/Army and the Garrett/Navy programs made substantial progress, neither resulted in completely successful engine demonstrations. Following problems in the Garrett program that appeared to preclude reaching the demonstration goal of 50 hours, the author was tasked by DARPA to conduct an assessment of using ceramics in heat engines. The starting point of this assessment was why the recent Garrett/Navy program failed to reach its demonstration goals. However, the assessment was directed to go well beyond this and consider the application of ceramics to heat engines in general, not just turbine engines. This broader context was also to consider the spectrum of materials issues, e.g. the possible use of carbon-carbon materials. While greater emphasis is placed on materials and uses more pertinent to DoD applications, commercial and consumer applications are also addressed.

Before proceeding to the assessment, a few words about the methodology, then some background on ceramics in heat engines are given. With regard to the methodology, a day long meeting was held at Garrett focusing on the problems encountered in their DARPA program. Participants at this meeting included most persons having had extensive contact with the program. Following this, the author made extensive visits to most of the major organizations in this area and made extensive contact with individuals by letter, phone, and at meetings. Since the topic is very broad, the purpose of the text is to provide key background information. It is not possible to provide extensive documentation and background on all conclusions and recommendations.

Manuscript submitted February 17, 1981.

B. Ceramics for Heat Engines

The primary motivations for using ceramics in heat engines are their potential for improvement in performance (i.e. increase efficiency and/or power) reduction in cost, and reduction in use of scarce materials.* Use of ceramics may also provide chemical benefits, e.g. multi-fuel capability, and reduced erosion/corrosion for longer life. The extent of the payoff in each of these areas depends on the particular application. Significant attention has been appropriately focused on key hot section components; primarily vanes or nozzles and blades in turbine engines, and pistons or piston caps and cylinder liners in diesel engines. Such components can make large impacts in power per unit weight or volume and/or fuel efficiency, e.g. 30-50% improvement in the latter. However, a variety of lesser, but nonetheless, important potential advantages can accrue from the use of a variety of other components including shrouds, seals, combustors, bearings, precombustion cups, valve lifters, cams and turbocharger wheels. A particularly important accessory component for many turbine applications is a heat exchanger. Their utility arises from the fact that as ceramics are used to increase engine operating temperatures, the full efficiency benefits of those increased temperatures are not realized without the use of heat exchangers (or combined cycles) to recover heat from the otherwise increased exhaust temperatures. The development of ceramic (silicate) rotary heat exchangers was an important technological advance for present (metal) truck turbines. Such exchangers are also an important factor in the large projected efficiency improvements of using ceramics in key hot section applications in turbines for cars. However, a recent study+ shows that much broader use of

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*To some extent, cost reductions and reduction of scarce strategic metals can be a double accounting, i.e. under many conditions increased scarcity of metals will increase their price and hence improve the potential cost advantage of ceramics. However, under embargo or similar curtailment of supply, the advantage of reducing demand for critical materials can extend significantly beyond the market generated economic advantages.

+"Proceedings of the Workshop on High-Temperature Materials for Advanced Military Engines," Vol. I- Workshop Discussion and Summary, Vol. II - Technical and Programmatic Presentations, Donald M. Dix, John E. Hove, and Frederick R. Riddell, eds., (Sept. 1979).

heat exchangers in conjunction with high engine temperatures achieved by use of ceramics could have large impacts on a number of key DoD applications. A number of these heat exchanger applications would require higher temperature ceramics of the same types as those being investigated for turbines themselves. Both these applications and materials are very closely related to development of ceramics for large scale industrial heat exchanger applications, e.g. for large energy savings in the steel industry.

The focus of this assessment is on key hot section engine components. However, much of this report also directly or indirectly bears on these other important component or heat exchanger applications, which have most of the same design and especially material issues in common with key hot section components. Further, it should be noted that the combined effect of successful usage of ceramics in this range of related applications has important national implications, e.g. as suggested by later comparison to the Synfuel and large scale electronic integration technologies.

Critical questions in ceramic heat engine applications are whether this can be done with adequate reliability at truly competitive costs. Reliability issues reflect both the combination of the brittle behavior of ceramics and their uncertain strength in aggressive engine environments and the uncertainty of whether we know all the necessary details of the environmental requirements. These uncertainties must be weighed against the central payoffs and the alternative routes to achieving at least part of the desired goals from utilizing ceramics. A major conclusion is ceramics can be used for important initial applications, but that both the opportunity and need exists, to go significantly beyond current capabilities to obtain a broader range of applications and still greater payoffs.

II. ASSESSMENT OF THE CAUSES OF ENGINE FAILURES IN THE DARPA/NAVY/GARRETT PROGRAM

While any assessment of this program must focus extensively on the serious engine failures that occurred and precluded the program from reaching its demonstration goals, it is appropriate to first briefly review some of the important positive aspects of the program. Important contributions in the following areas are a direct result of this program: 1) design with brittle materials, e.g. successful demonstration of spin-proof testing of ceramic blades in a metal disk, 2) design of turbine engines, e.g.

combustor dynamics and engine thermal transients, and 3) material processing, particularly in the area of surface finishing, material characterization, and nondestructive evaluation. Further, the program came reasonably close to demonstrating the power and fuel consumption improvements that were targeted (Table 1). This is a milestone in that this was a first time that the projected benefits of using ceramics had been demonstrated in practice. (While the Ford program demonstrated a number of hours of successful engine running at high temperatures, it was with incompletely bladed rotors and hence did not demonstrate power/efficiency improvements). A particularly important outcome of the program, as discussed below, is that the ceramic bladed metal rotors appear to have been successful.

Despite these important outputs of the program, the disappointing fact remains that the program experienced major engine failures* which precluded the program from achieving its 50 hour demonstration goal within the original funding limits. While earlier, lower power, failures were solved by going to a much gentler light - off cycle, subsequent failures were mainly shortly after going to full power conditions. Further, static and rotating components respectively successfully passed overstress static and rotating rig tests. Thus, while the failures occurred, and were very disappointing, the above suggest that while the goal was missed, it is achievable.

Two important factors emerge from the following summarized assessment of this program. First, the ceramic bladed metal rotors appear to have been completely successful, i.e. were a success hidden by the failures resulting from the static components. Second, there is a clear need for better understanding and control of interfacial phenomena, i.e. between ceramic components and ceramic or metal components whether or not they have an intervening complaint layer.

Consider first the evidence that the blades were a success and not the source of engine failures. In the one rig test in which a blade did fail (due to an identified, and subsequently eliminated, vibration problem), it failed down in the attachment region, the expected region of

*An important outcome of the failures themselves is that they demonstrate that there is no serious problem to failure containment. This, for example, appears to make it feasible to use a sheet metal housing rather than a heavy cast housing for turbochargers with ceramic wheels, thus saving significantly both in weight and cost.

TABLE 1

ARPA/NAVY/GARRETT CERAMIC TURBINE ENINE PERFORMANCE

	T76 (Uncooled Metal) Engine	Ceramic Engine	
		Goal*	Achieved+
Power Output (Shaft Horsepower)	715	1000	930
Specific Fuel Consumption (lb/hp-hr)	0.60	0.54	0.56

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*With 0.025" tip clearance design.

+With tip clearance opened up to 0.050" as an initial conservation step.

failure, because of the significant maximum stress there. The failure of this one blade then "cobbed" the rotor; i.e. broke off all the rest of the blades above their platforms. All of the remaining blade stubs showed significant impact damage from the fragments of the first and subsequent failed blades. In the engine failures, all blades were "cobbed" with no failures down in the attachment region strongly arguing against any bade failure in view of the relatively low stress in the blades above the platform and the fact that all blades had successfully past an overspeed proof test. Further, blade stubs showed significant evidence of particle impact and Garrett testing had demonstrated that impact of reaction sintered silicon nitride (RSSN) chips as small as about 2 grams can destroy a blade. The apparent success of the ceramic bladed metal rotor in the Garrett program is supported by the successful spin testing of a ceramic bladed metal rotor at Pratt and Whitney.

On the other hand, considerable evidence points to static components as the source of failure. First, lower strength of the static, RSSN, components meant that the ratios of strength to peak design stresses were less than 150% and in some cases possibly as low as about 120%, in contrast to approximately 200% or more for the hot pressed Si_3N_4 blades. Second and more specific is the fact that in some engine tests, static components were found to have cracked or chipped during the run but with pieces retained so that they did not lead to complete engine failure. Also, earlier work associated with lightoff problems had revealed that the RSSN static hardware was being damaged, i.e. cracked or broken due to thermal transients from lightoff showing the marginal capability of the RSSN components vis-a-vis the hot pressed blades*. It appears extremely probable that similar cracking during engine runs resulted in complete engine failure due to cracked pieces falling into the flow path. This could result from their location not allowing them to be held in place after cracking or due to vibration, or to thermal growth, or contraction with changing temperatures. As noted above, Garrett tests show that relatively small chips of RSSN can take out blades and the resultant high velocity fragments would take out remaining static and dynamic components. It also appears highly probable that impact damage from ceramic chips would propagate both upstream and downstream in the engine so that a cracked or chipped piece from even a second stage vane, for example, would most likely take out the entire engine.

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*As noted earlier, these observations led to a modified lightoff cycle to minimize such thermal transients.

The important question then is what was the cause or causes of the failure of the static (RSSN) components. Contact stresses, due to point loading, accentuated by uneven load sharing between components and motion between components appear to be the primary and possibly the exclusive source of this failure. This conclusion is based on three key observations: 1) where cracking has been observed in static components, it typically appears to be associated with contact points, 2) the large number of static components and the associated large number of interfaces provided both a large number of contacts as well as high potential for significant variation in the contact loads due to unequal load sharing, e.g. as a result of minor component shifts during thermal growth, and 3) Garrett's subsequent testing clearly demonstrates a significant susceptibility of RSSN materials to contact loading damage sufficient to cause component failure, especially with some lateral motion such as that due to thermal growth. Transient thermal stresses, such as those due to hot streaking may also have contributed to these failures, as suggested by uncertainty in the thermal analysis (discussed later) and there clearly were problems due to the start transients noted earlier. Some members of the assessment team at the Garrett meeting also raised the question of whether or not vibration in the engine may have accentuated contact failures since static components survived over pressure rig tests, i.e. without rotating components and attendent potential vibration. While vibration in static metal components is normally not considered to be a problem, some felt that this was a relevant question to ask in view of the vibration sensitivity of contact problems Garrett tests have shown in conjunction with the rotor failure noted above. Ceramics have sufficiently different vibration characteristics from metals, and less background, e.g. effects of interfaces, on vibration, that some investigation of vibration of ceramic static components may be warranted.

The apparent success of the ceramic bladed metal rotors has two important ramifications. First, it demonstrates the utility and importance of broad, bold demonstration programs such as the Garrett program. This results from the fact that this author and I believe a number of other individuals closely following the Garrett Program felt much greater uncertainty about the rotating components at the beginning of this program, yet these appear to have been the successful components. Second, the apparent success of the ceramic bladed metal rotor needs definition, i.e. it needs to be clearly verified and its extent determined in terms of temperature/life capability.

The apparent success of ceramic bladed metal rotors is important from a practical standpoint since there are a variety of important applications in which use of only ceramic blades would provide significant benefits. Wherever air cooling is a viable option, vanes can often be more easily cooled than blades, and the power/performance penalties of cooling vanes is typically less than that of cooling blades. Air used to cool vanes can be reintroduced into the gas stream to deliver some work on the corresponding stage of blades whereas the air used to cool blades cannot be used to produce any work on the corresponding stage of blades. Thus, if one is dealing with a single stage engine all of the heat absorbed in cooling blades is lost. Further, blades have the important advantage of having the one definitive quality assurance technique applicable to them; namely, spin-proof testing. Also blades see less extreme and more uniform temperatures than vanes increasing their margin for success. Specific program(s) to define the success of ceramic blades in a metal rotor is therefore recommended.

The above discussion of the importance of ceramic bladed metal rotors should not be interpreted as recommending neglect of ceramic static components. To the contrary, static components are not only important, but in many cases critical to a variety of important ceramic applications to turbine engines. Hence the static component problems need to be directly dealt with. In the near term, the greatest payoff is expected to come from direct empirical study of interfacial and contact phenomenon and observing other static component interface approaches, e.g. on the DDA CATE program. However, it appears essential that longer term, more basic research also be initiated to provide an essential basis for further developments beyond the expected useful near term payoff of the suggested empirical work. Development of tougher ceramics, more resistant to contact damage, e.g. as suggested by newer composite ceramics can also be very important. The importance of studying and handling interfacial problems will be noted in discussions of other programs.

III. OTHER CERAMIC ENGINE PROGRAMS

While the focus of this section will be to review key elements of existing ceramic engine programs, it is useful to first briefly consider past programs. The first program on use of ceramics in turbine engines in the U.S. started in the middle 1940's in response to Allied information indicating that the Germans might be conducting similar work to improve the performance of their jet engines. Two leading candidates initially involved in this U.S. program were apparently a BeO based "porcelain" material and sillimanite (Al_2O_3-SiO_2) (Table 2). Complete ceramic bladed metal rotors were made and tested to temperatures of approximately 1800°F (Fig. 1A). Rotors could apparently sometimes be brought successfully up to temperature and speed, but failures often occurred, e.g. on cool-down. The next phase of this work in the 50's was development of cermets (Fig. 1B) which also proved unsuccessful (Table 2). It is, in fact, this lack of success which apparently gave cermets their bad name, i.e. that they represented the combination of the worst properties of metals and ceramics insted of their best properties. (This is a misleading representation for other uses, e.g. cutting tools.) During these periods, there was also some effort to utilize ceramics (apparently, typically Al_2O_3 based materials) in internal combustion engines including both pistons and cylinder liners.

An important question is what has changed in the intervening years to make the prospects of using ceramics in heat engines successful. Four key changes can be cited. First, and foremost, is that the driving force has significantly increased, and will continue to increase, creating a much greater need for efficiency as well as the important need to reduce use of scarce materials which in many cases also translate into added economic advantage of using ceramics. Second is the significant difference in design technology, particularly the availability of computers and finite element techniques. Although, as noted elsewhere, these techniques need further development and improvement, they are clearly a major asset. Third, we have much better materials, i.e. materials with the combination of higher strength, toughness, and lower thermal expansion (to limit thermal stresses), Table 2. Fourth, though much remains to be done, we have made important strides in design-material evaluation capabilities based on fracture mechanics, including the developing technology of proof testing and/or nondestructive evaluation coupled with emerging life prediction methodology.

The key question is of course whether or not these improvements are sufficient to make the use of ceramics in heat engines successful. It is the judgment of this author that we now have the materials and technology for useful introduction of ceramics in heat engines, e.g. as suggested in the current ceramic heat engine programs. Blades appear most promising in the near term from the standpoint of demonstration, quality assurance, and payoff, but success,

Table 2

PROPERTY TREND SUMMARY FOR CERAMIC TURBINE MATERIALS

Material	Approx. Tensile Strength (10^3 psi) at: 1800°F (980°C)	1900°F (1035°C)	2300°F (1260°C)	Thermal Expansion Coeff (°C^{-1})	Fracture Toughness (K_{IC}) (MPa m$^{3/2}$) at 22°C
A. Later 1940's					
1) Sillimanite (Al_2O_3-SiO_2)	19			7	($\leq$ 2)
2) BeO (porcelain) e.g. 48-11C (84.2 w/o BeO, 7.2 w/o Al_2O_3, 8.6 w/o ZrO_2) + 2 w/o CaO	13			(9)	(1-4)
B. Early-Middle 1950's					
1) 80 w/o TiC, 20 w/o Co		33	12	9	(5-10)
2) $MoSi_2$			40	8	(4)
C. 1970's					
1) RSSN			(20)	3	2
2) HPSN			40	3	4-6
3) HPSC			35	5	4
D. Middle 1980's					
1) Particulate Composites				(3-9)	(4-12)
2) Fiber Composites				(3-9)	(8-25)

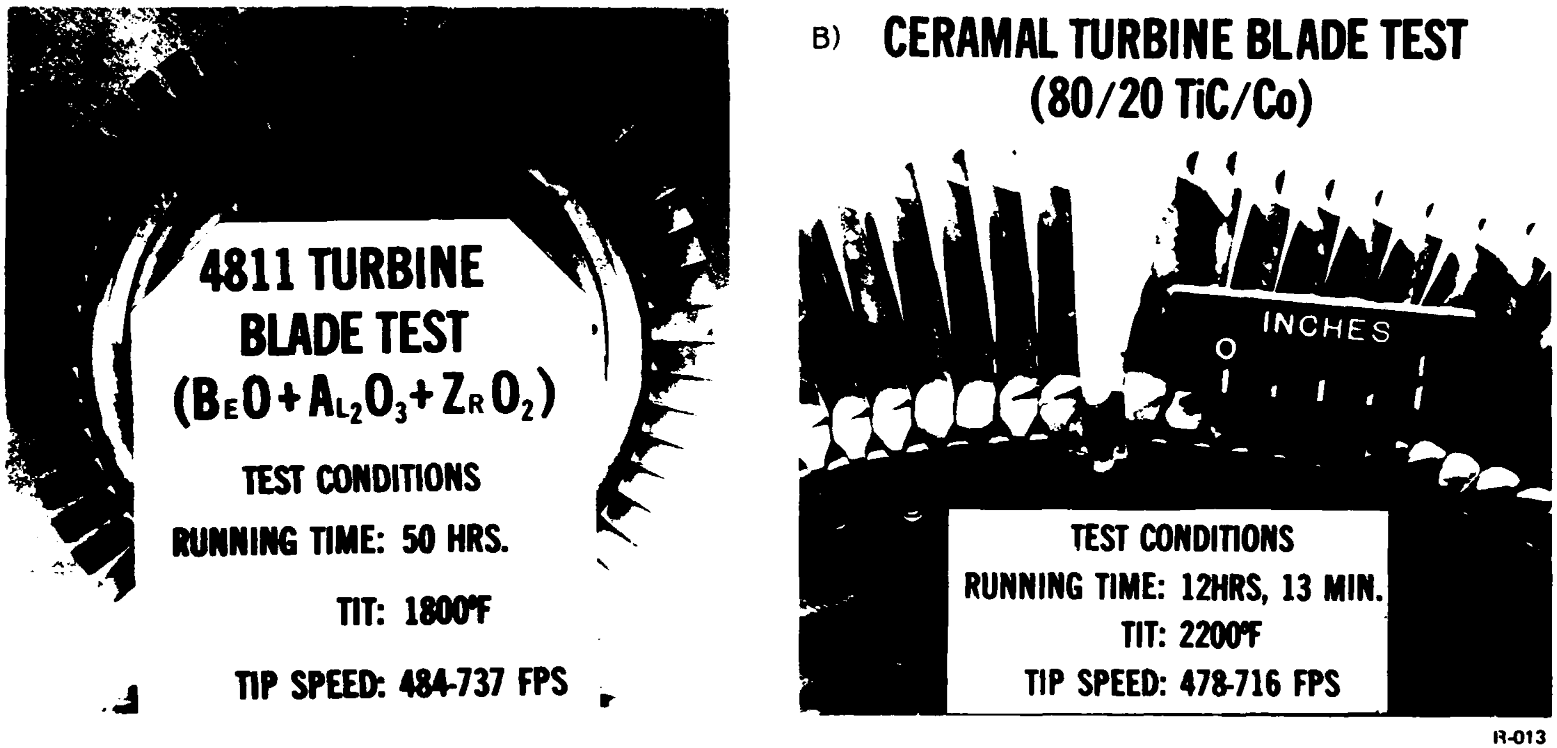

Figure 1. Earlier Ceramic Blades. A) BeO based "porcelain" blades in a metal disk for NASA (then NACA) tests in the late 1940's. Note temperature goal of 1800°F. B) Cermet blades in metal disk for NASA test in the 1950's. Note temperature goal of 2200°F. Ceramal was one of the competing terms with cermet to describe metal bonded ceramics at that time. Photos courtesy of Mr. James Gangler, NASA (retired)

e.g. in the Ford and Solar programs, indicate that some static applications are also at hand. Further, continued efforts on static materials and design should fairly rapidly remove many of their current limitations. However, continued development is necessary to progressively advance the extent of ceramic applications in both the number and character of applications, e.g. for higher temperatures and longer life.

The DARPA/Army/Ford-Westinghouse program was the first of the more recent and larger scale efforts to introduce ceramics in turbine engines*. This joint effort, which was the first large scale attempt to apply advanced design and material evaluation technologies, made major contributions to field. These include techniques for designing with, and fabrication, characterization, and testing of, ceramics.

The Westinghouse portion of the program focused on ceramic vanes for a power generating turbine, and hence dealt with much larger ceramic vanes than other ceramic turbine programs. While limited by funds to a few rig tests, the Westinghouse work demonstrated during a significant rig failure that hot pressed Si_3N_4 vanes could in fact withstand considerable impact and excessive thermal stress as a result of molten metal pieces impacting on the test vanes.

The Ford portion of the program was extremely ambitious, seeking to make an almost total ceramic automotive-scale engine. This program demonstrated that ceramics could meet the program goal of 200 hour durability over a duty cycle up to 2500°F by combined rig and engine testing. Although the program goals did not specifically include power and efficiency improvements, it is nonetheless disappointing that it did not demonstrate such improvements. The major limitation was the inability to completely solve problems in the complex fabrication of all ceramic rotors that were adequately free of defects (i.e. a final test was conducted with defective blades purposely broken off, hence precluding the engine developing anywhere near full power and expected efficiency). In addition to the basic technological developments noted earlier, a number of specific developments of this program should be noted. Of particular significance for this report was the success with RSSN static components including vanes, nose cones, and tip

*Approximate cost and time spans of the programs are shown in Fig. 2.

shrouds. The success of these static components is attributed to their extensive development and design, i.e. an integral, single piece, stator ring. Such a design was in part, allowed by the smaller engine size, hence minimizing or eliminating many of the interface problems encountered in the Garrett program. Ford also demonstrated extensive success with reaction sintered SiC (RSSC) combustors.

The next oldest program, the Army program with Solar, is unique from two standpoints. First the initial, i.e. ceramic nozzle vane, phase of this radial engine program was motivated by the need to significantly reduce dust erosion of vanes trailing edges rather than to increase temperatures and hence power or efficiency. The second unique aspect of this program is the excellent progress that has been made at modest cost (Fig. 2) by taking a step by step approach with a small engine over an adequate period of time. Considerable engine success has been demonstrated by Solar with two or three types of ceramic vanes either loosely mounted in the shroud or bonded in the shroud with glasses. One failure did occur in an RSSN shroud. Both the low macrostress and the very low stress indicated on the fracture surface suggests to this author that this failure may have been due to contact stresses. The fracture of the shroud was through the mounting pin and the fracture origin appears to have been in the vicinity of the pin itself. This engine has been run successfully with hot pressed Si_3N_4 vanes and NC430 SiC shrouds for 200 hrs. It is also useful to note the effect of the extremely simple vane shape on projected production costs as summarized in Table 3.

This program is now entering a more extensive phase. The present 10 kw unit will be scaled up to 15 kw by increasing the average turbine inlet temperature (TIT) from 1650 to 1950°F and use of a metal recouperator, i.e. demonstrating the importance of exhaust heat recovery. This power upgrading may include consideration of a ceramic radial rotor. Apparently, limited further expansion of this engine's power could put it in the approximately 30 hp range, i.e. adequate for small car propulsion.

The DoE-Westinghouse and Garrett Ceramic Technology Readiness Programs for power generating turbines using ceramics for high temperature-increased efficiency have completed Phase 1. Efforts under Phase 2 are under consideration (and hence are not reflected in the funding shown in Fig. 2). This is an ambitious program in that the important opportunities and needs in the power generation field are particularly demanding on component life and reliability. This, combined with the significantly larger size of

Table 3

Ceramic Component Costs

	1977	1980	Mid 1980's
Garrett HPSN Blades	$1000	$400-500	$150
Garrett RSSN Vanes	1000	200-400	35

Solar Radial Engine Vanes

Cost per vane for Purchase of:	1000	10,000
HPSN	$13.4	$13.4
SSN (Injection moulding)	28.8	23.1
SSC (Slip cast)	---	7-10
RSSC (Slip cast siliconized SiC)	5.0	2.5

most components, presents particularly challenging goals for design and especially material capability. It is in fact this author's understanding that the intent of Phase 2 was to squarely address this large material development issue but that there may be serious uncertainties in the feasibility of adequately justifying the necessary material development effort both in terms of adequate time and dollars, within the confines of presently perceived organizational needs. Such a comprehensive material development program, properly conducted, would not only be necessary to meeting the goals of this turbine power program but would have wide impact on most heat engine program needs because of the extensive commonality of the basic needs. Further many developments that did not meet the more demanding requirements of this program could have important spin-off and utilization in components of other less demanding applications. This difficulty of justifying, within the narrower confines of a particular group's mission, a major materials effort needed for this and other programs illustrates an important institutional or administrative issue that must be resolved to adequately develop ceramic technology for heat engines.

The Air Force/Garrett program, in many respects is the first major iteration of the DARPA/Navy/Garrett Program. It represents a significant simplification, being a single stage engine, allowing much simpler supporting of the ceramic static components. However, the goal of this program, though limited in funds, is to address key aspects of component manufacturability. The engine demonstration is to verify the manufacturing process. This program which is oriented towards possible future cruise missile engines is just now entering its rig testing phase. There have been some initial cracking problems with RSSN vanes, but it is too early to tell how serious these are. There are some implications that thermal stresses, e.g. from hot streaking may be an important factor in these initial cracking problems but contact stress effects or other problems apparently cannot be finally ruled out at this stage. If these static hardware problems are solved, this program would provide additional demonstration of ceramic bladed rotor success as well as, of course, added demonstration of static component success. Some useful manufacturing information, e.g. progress in hot pressing blades to near net shape has already been achieved (see Table 3). Also, the strength-reliability of slip cast RSSN has been improved.

Consider next the DoE/NASA CATE program at Detroit Diesel Allison (DDA) which is to develop an approximately 400 hp ceramic axial turbine engine for demonstration in truck and bus applications. The focus is on sintered materials because of their potential low cost. This program, which at the time of its initiation was one of the biggest programs, has been progressing in a staged fashion focusing more on vanes in the initial stages before incorporating the ceramic bladed metal rotor. Thus far sintered SiC replacing every other metal vane have been run in an extensive road test at intermediate temperatures. The attachment of the vanes both in the existing metal structure as well as the ultimate all ceramic vane structure is a loose mounting as opposed to tight contact in the Carret engine. While future problems may be encountered, the success to date again indicates that static components can be successful.

The Teledyne Excentric* engine program in which a single eccentric stage utilizing ceramics only as blades in a metal rotor may provide further important verification of the potential utility of ceramic bladed metal rotors. Sintered alpha SiC was selected for this application because of the high TIT (2500°F) average temperatures, making this a challenging program. This program is also one of the few to consider use of ceramic coatings, but only as an oxidation resistance (silicide) coating on the refractory metal vanes.

The three newest and largest ceramic turbine programs are the DoE-NASA radial engine AGT programs for automotive power (Fig. 2). These programs are directed towards developing efficient turbine engines (e.g. 40 mi/gal) to power 3000 lb.-plus automobiles, which in the 1985 frame, when the program will be completed, will be the heaviest and hence amongst the largest automobiles expected to be built.+ These programs are emphasizing sintered SiC and Si_3N_4 and should significantly aid their development. However, both the fact that these are challenging programs and that by definition they represent alternate, i.e. not the prime engine choice of the auto companies, leaves important questions of the extent to which they would be translated into practice, i.e. production. However the presence, and

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*Trademark

+Both German and Japanese ceramic turbine programs for autos are considering engines for cars of this or somewhat greater weight. The emphasis on larger cars apparently is based on part on this being an easier market sector to introduce such engines, both from an economic and a technological standpoint.

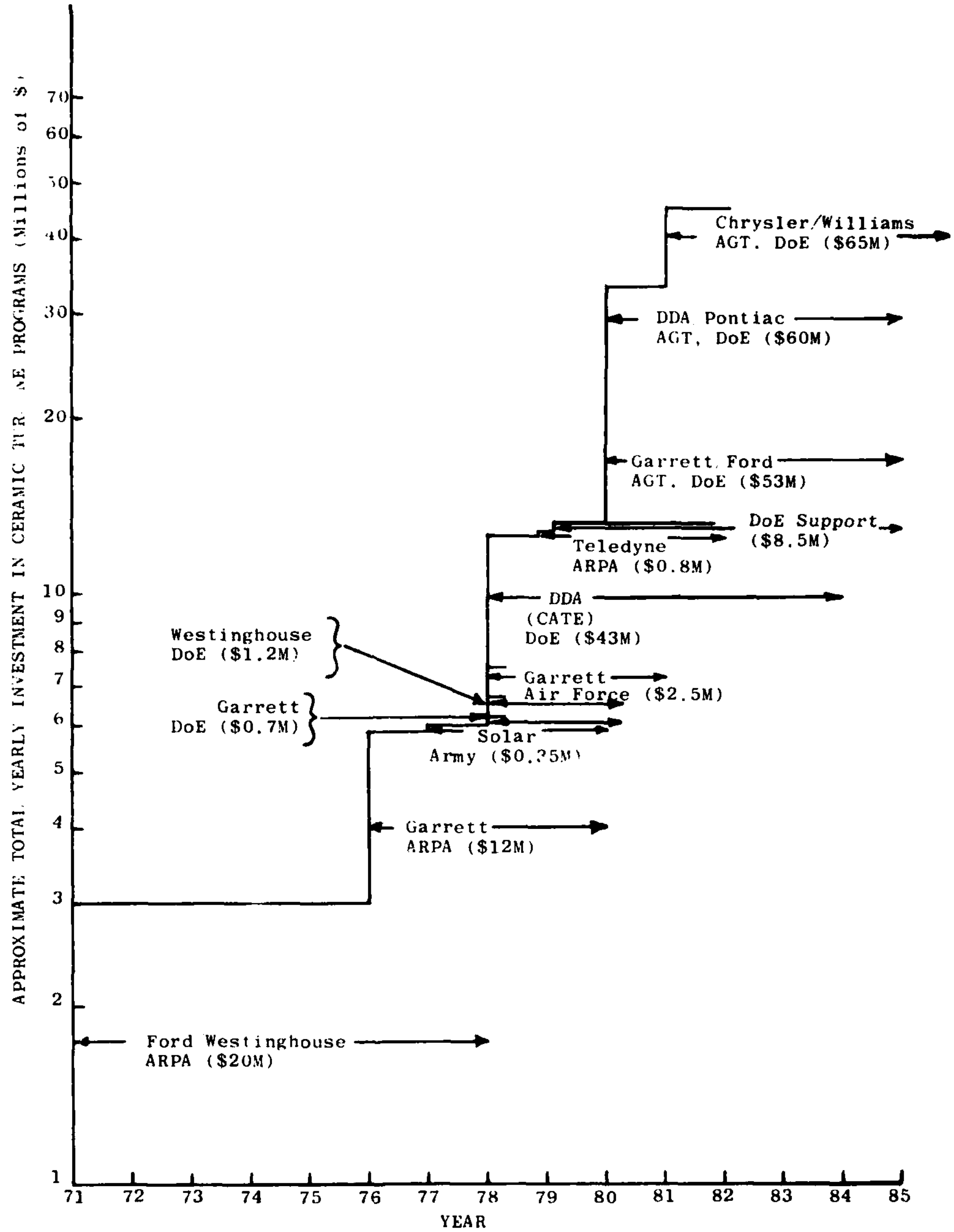

Figure 2. Investment in Ceramics for Turbines. Note that the rise of funding with the initiation of a program does not necessarily reflect the funding on that program, since it may also be effected by reduced funding due to completion of other programs. Horizontal arrows define the time of a program and the approximate total funding is shown in (). Note the possible Phase 2 funding for the DoE power generating turbine (Ceramic Turbine Readiness) program are not included since the status of this program is uncertain.

attitude, of turbine engine manufactures in these team programs is encouraging.

The other major engine program, the Army/Cummins program is the only major piston engine program in the U.S. (Carborundum and possibly other firms are conducting some work on components such as valve lifters for piston engines). The immediate goal of the Cummins program is an adiabatic turbo compounded diesel engine. A subsequent goal is to make this a minimum friction engine. This aggressive program is oriented around the substitution of key ceramic components in the large (400 HP) six cylinder diesel truck engine, with the most critical components being ceramic piston caps and ceramic cylinder liners. Two sources of successful piston caps have passed all single cylinder engine testing; namely hot pressed Si_3N_4 caps from AMMRC and from Toshiba. While some initial problems in shrinking hot pressed Si_3N_4 cylinder liners into metal sleeves were encountered,* subsequent tests of ceramic cylinder liners appear to be progressing well. (Although at least one commercial source was sought thus far, the only successful supplier of a hot pressed Si_3N_4 cylinder liners was Toshiba.) This program represents an excellent initial evaluation, and suggests important opportunities to be explored with subsequent material development.

IV. DESIGN ISSUES

Several design issues need to be addressed. The broadest and most general need is for design verification and iteration. In view of the complications found in complete engine programs to date, emphasis for such verification should more appropriately be placed on one or two types of components in engine or rig type tests. While tests of vanes deserves consideration, the apparent success and potential greater utility of blades, or wheels (e.g. for radial engines or turbo chargers) suggest these as good candidates for near term tests. Such tests should verify predicted safe operation by successful running at design conditions, which may require some design iteration. Running conditions should include start and shut-down transients as well as steady state. After successful demon-

*Analysis of this failure by the author and colleagues indicated that it represented a contact stress type failure.

stration, sufficient components should be run to failure both by going beyond short term design parameters, i.e. going beyond normal transient and steady state parameters, as well as testing to failure after various service times to verify life capability. Both because of cost as well as the beneficial impact on manufacturing/quality assurance, such a program may be best done in conjunction with manufacturing development programs. Such programs should emphasize sintered materials, but hot pressed and possibly hipped materials should be considered for comparison.

Two related general design issues are the integration of ceramic coatings and monolithic ceramics, and use of monolithic ceramics for purposes other than just temperature, and performance increases. Ceramic coating and monolithic ceramic programs are typically totally separated. However, in view of the nearer term and somewhat greater payoff of monolithic ceramic blades, use of ceramic coated metal vanes with them, deserves broader consideration. Such mixed usage should also be considered in determining the number of stages, work split, and materials for multi-stage engines. Coating usage has been predicated as much or more on issues other than performance, i.e. mainly corrosion and life issues. However, monolithic ceramics have not apparently been similarly considered, except in the Solar program. Such applications for monolithic ceramics could offer valuable payoff for such specific applications as well as in the ceramic experience gained, e.g. in design, performance, and manufacturing.

Another broad design issue is that of combined cycles and heat recovery. Using ceramics to increase operating temperatures can provide increased performance. However, it also often increases exhaust temperatures, so heat exchangers or combined cycles are needed to fully realize the full potential performance improvement. The IDA High Temperature Materials for Advanced Military Engines workshop and the Cummins Adiabatic Turbo-Compounded Program are examples of this approach. The increased consideration being given to heat exchangers, e.g. in the DoE, CATE and AGT programs is to be encouraged. However, broader consideration of payoffs with compound cycles appear needed. Thus for example, DDA reports a significant (e.g. > 25%) down sizing of their AGT turbine engine by using an oversized starter that can also provide an electrical boost to drive train power for aiding the initial stage of acceleration. This and the typical idle penalties for turbine engines (e.g. approx. 2 mi/gal) suggests that a more detailed look be given at hybrid turbine-electric auto systems. Such development might be further aided by recently announced advances in batteries for electric cars. Hybrid (or other) design studies should also consider the extension of turbines to smaller cars. The Solar turbo-alternator might serve as a useful model.

An important, more specific design issue is how to improve our ability to analyze and hence design for multiple interacting components and the resultant contact stresses. As noted earlier, finite element techniques cannot be considered absolute calculations, especially at this stage of development for contact problems, and many people feel that the analysis of contact stresses will require very extensive development. There are, in fact, investigators who feel that fully adequate handling of these stresses may not be achieved by finite element methods, e.g. boundary integral equations techniques have been suggested as an alternative. Two other related issues are: 1) the design of interfaces to minimize contact stresses, e.g. to assure that contact must always occur at more than one point under all possible component orientations, and 2) to predict the various combinations of orientations and uneven loadsharing amongst various groups of stacked or otherwise contacting components.

Another issue is the question of developing other designs. The emphasis to date has been on axial engines, but AGT programs focused on radial engines will more than balance the relative degree of study. Beyond this, other design approaches, especially novel ones are needed, and should be a continuing endeavor. However, it is concluded that the extensive implementation of ceramics in heat engines can be done with conventional designs and does not require a basic design innovation, e.g. consider ' ındi-cated success of ceramic bladed metal rotors in the arrett and Pratt & Whitney programs, and successful runs of all ceramic turbine wheels at Ford. This does not say that new innovative designs would not be welcome nor useful. However, they are likely to require substantial development, and may not solve issues now impeding implementation of ceramic uses in engines. Thus, for example, important questions must be answered about the possibility of putting ceramic blades in compression.

Putting blades in compression has some very desirable aspects, but there are also some important questions about this. The contact stress problem in existing engines is basically a problem of tensile stresses from compressive loading. Further, this type of problem is also suggested by compressive testing wherein end finishing of specimens and extreme care in alignment are necessary to avoid high localized tensile stresses at the compressive loading surfaces. These parasitic tensile stresses often dominate the failure of specimens in compression testing. Similar problems could occur at attachments of blades in compression. Further, there is evidence that suggest that damage starts developing in specimens under compression loading at a relatively small fraction, e.g. 1/3, of their ultimate compressive strength. This may well be an intrinsic effect due to elastic and thermal expansion anisotropy, and suggests for example that compressive fatigue-like behavior could occur with repeated compressive loading near, and possibly substantially below this approximate 1/3 ultimate compressive stress level. Some experimental evidence exists for such effects in softer ceramics, e.g. ZnSe and lead zirconate titanate.* The absolute loads at which such damage may occur in high quality ceramics probably should make their use in compressve loading quite safe. However, these phenomena would suggest that the use of lower strength material such as reaction sintered Si_3N_4 may be no more feasible with compressive than with tensile loading.

Despite the above suggested compressive loading limitations, novel designs need to be explored on a research basis. At least one concept for utilizing ceramic blades in compression with apparently quite modest compressive loads was found during this assessment. Interestingly, this approach would achieve compression in ceramic blades through the use of carbon-carbon materials.

V. MATERIAL ISSUES

A. Manufacturing Technlogy/Conventional Si_3N_4 and SiC Materials

Existing materials based on reaction processing or additive densification of Si_3N_4 and SiC bodies appear adequate for useful limited life engine applications and some of these show potential for longer life systems. To put the existing capability in practice and to also continue to expand the operating capability of ceramic materials three areas of R&D are necessary. These are: 1) R&D of the conventional materials and processes; 2) development of

*"Compresive Strength and Acoustic Emission Behavior of Navy Type I Ceramics," Appendix A in Proceedings of the Workshop on Sonar Transducer Materials, pp. 231-235, Paul L. Smith and Robert C. Pohanka, eds., (Feb. 1976).

manufacturing technology for selected materials and processes; and 3) development of other materials (which will be discussed in the following section). R&D of conventional materials is the only one of these three areas receiving substantial, though not necessarily adequate, support.

The critical need and major deficiency in this area has been the lack of the necessary manufacturing technology development based on conventional powder processing approaches. There is no doubt that if ceramics are to be successfuly used in heat engines within the next several years, the materials used will be made by powder processes. While the extensive R&D programs as well as the demonstration programs have been and will continue to improve the base line from which manufacturing technology can be developed, a truly concerted effort on the manufacturing requirements has been lacking.

The criticality of manufacturing technology to the success of ceramics in heat engines can be seen by recognizing two central points. First, ceramics (and composites) are unique in that the dependence of the resultant properties and reliability of the finished product depends not only on the processing technique by which they are made, but also on the specific size and shape of the component and the interrelationship of these factors with the material and the processing technique itself. This is most critical in ceramics which do not have as high a level of fracture toughness as composites to make them more tolerant of processing defects. Further, the manufacturing technology will typically be the dominant issue in the economics of ceramic components, which will often be the pacing issue in their application, especially in any successful commercial introduction of ceramics to heat engines.* Secondly, it is essential to recognize that there can be significant differences between actual manufacturing and present laboratory or demonstration scale programs.

The most significant difference between actual manufacturing and laboratory or demonstration programs revolve around <u>dedication</u> and <u>specialization</u> of both people and equipment. In an actual manufacturing program, equipment can be dedicated not only to that program but in fact to specific compositions. Thus, for example, storage, handling, mixing, consolidation, firing, etc. facilities can be dedicated to a specific process-composition. This dedica-

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*Note that the scope of DoD needs is often limited, such that DoD usage often depends on successful commercial use to make the technology available.

tion avoids, for example, cross-contamination as a result of inadequate cleaning or protection from other compositions or entirely different compounds being processed in a given laboratory.

Specialization is equally important and takes several forms from the standpoint of both human endeavor and facilities. Consider first the facilities. Once a specific composition and process is established, facilities can be specilized for this in a variety of ways. Thus, for example, wear of materials in processing facilities can be specifically designed to provide minimum degradation of a particular process. Milling media, ball mill liners, die cavities, setters, etc. can be especially selected to provide minimum interaction or degradation with the components being manufactured. Equally important, dedicated systems can be highly specialized for the selected process composition combination. This can include for example specialized heating profiles in injection molding dies, and firing furnaces. It should also be obvious that the dedication and resultant specilization of personnel assigned to a particular process in association with the above facilities is an important factor in improving the overall process. It is, for example, suggested that in at least some ceramic components greater degrees of reliability can be achieved in manufacturing than in any laboratory environment because of the combinations of these effects. Manufacture of spark plugs which is probably one of the highest reliability, large volume, technological applications of ceramics is often cited as an example of this.

There are other critical or highly beneficial results that would accrue from establishing actual manufacturing of one or more ceramic components. As will be discussed in Section VII, obtaining one or more viable ceramic products either in heat engines or using the same materials and technology in other (e.g. coal gasification) systems may well be a critical necessity to maintain the availability of U. S. technology to put successful engine demonstrations into practice. Such production would provide the necessary maintenance of both a raw material supply as well as the actual fabrication technology itself. The other fundamental benefit of establishing production manufacturing capability is that it provides a base line for much more accurate extrapolation of capabilities, both in terms of technological as well as economic variables. Further, it provides a real basis from which further development of both material and manufacturing capabilities can evolve.

The large DoE CATE and AGT programs will significantly help in the manufacturing/process development. However, these are not seen as sufficient. First, they cannot provide the necessary level of material/manufacturing funding. Second, although they appear to go well beyond the restricted test component purchase approach of many of the previous programs, their goal is engine demonstration, not manufacturing. Third, while these programs hopefully will be successful, their complex nature due to extensive ceramic introduction in one step is very likely to result in demands that will limit the extent of manufacturing experience gained.

B. Other Materials R&D

Materials R&D for ceramics and heat engines has been almost exclusively focused on a relatively narrow range of reaction or additive processed materials. There are important possibilities both in considering a wider range of approaches to these more conventional type materials as well as new material approaches. Consider some examples of evolution of existing processing. SiC is densified with nonoxide additions, while Si_3N_4 is typically densified with oxide additions whose reaction products are typically associated with the high temperature strength limitations. This would suggest the possibility of seeking nonoxide densification aides for Si_3N_4. To date only one program (at General Electric) has investigated a nonoxide additive for Si_3N_4 showing significant improvement in high temperature properties, but at the expense of some room temperature properties. However, there is no indication that sacrifice of some room temperature properties is essential, in fact some interruptions of the data would suggest the contrary, i.e. that room temperature properties can also be improved. Another important example for evolving existing materials is chemical vapor deposition (CVD). It is clearly established that this process has the potential for producing excellent, if not the best, high temperature properties in SiC and Si_3N_4. However, besides the important questions of reproducability associated with this process (as with many of the other processes) microstructural control and elimination or minimization of residual stresses have not been seriously addressed to make this an important alternative process.

Turning to new materials, there are three categories to consider: ceramic composites, new compounds and carbon-carbon materials. Basically there are two types of ceramic composites, the first are particulate composites, i.e. ceramic matrices in which one or more ceramic particulate phases are dispersed. Phase transformation toughening and/or microcracking are important toughening mechanisms in such composites. The other type of ceramic composite is fiber composites wherein ceramic fibers are placed in a ceramic matrix. While both approaches have been around for a substantial time, significant development in both concepts as well as processing capabilities, particularly the fabrication of fine diameter high strength fibers, have opened up significant new opportunities in this area (e.g. see Table 2). Further, there appear to be important opportunities not only for developing each type of composite separately, but also for potentially combining the two types of composites. Thus far these composite systems have demonstrated capabilities for making up to approximately 10-fold increases in fracture energy via the particulate composite route and up to, or in excess of, 100-fold increases in fracture energy via the fiber route. Both types of composites could have important nearer term applicability to diesel and other piston engine applications as well as to possible turbocharger applications.

Present ceramic fiber composites do not yet have the temperature capability to meet the more demanding hot stage turbine applications but there appears a good chance that they will with further development. A major factor in the development of ceramic fiber composites has been the development of fine high strength SiC fibers in Japan. Significant recent polymer chemistry advances by at least one U.S. firm may further significantly improve the quality and lower the cost of SiC fibers as well as have other important ramifications in a number of ceramic processing areas pertinent to the use of ceramics in heat engines. The rapid and exciting development of ceramic composites thus appears to offer very important opportunities for ceramics in heat engines. However, more needs to be done on many of these composite systems before they would be at the stage for implementing into engine programs. On the other hand, the conventional materials should be capable of performing a number of important functions in heat engines and may often have significant economic advantages over the composites.

Materials effort to date for major hot section components has been on binary compounds, e.g. those compounds consisting of two types of atoms, e.g. Si_3N_4, and SiC. However, as discussed elsewhere,* there should exist many ternary and higher order compounds, some of which may have

*"Overview of the Naval Research Laboratory Ceramic Turbine Materials Program," R. W. Rice, pp. 613-624, in Proceedings of the 1977 DARPA/NAVSEA Ceramic Gas Turbine Demonstration Engine Program Review, John W. Fairbanks and Roy W. Rice, eds., (March 1978).

better properties for these applicatons. Definitive German R&D work, and apparently some Japanese work, has started in this area which may be very important to long term development.

Carbon-carbon (C-C) materials, because of their versatility in fabrication and high toughness, also offer interesting opportunities for applications in heat engines if adequate oxidation protection can be obtained without excessive loss of their toughness. A number of R&D level exploratory programs are now underway to investigate such utilization. Such programs are necessary before considering the launching of any major programs since crucial the question of whether truly adequate oxidation protection can be achieved must be answered. The present assessment is that it may be feasible to achieve adequate oxidation protection for short life engines; however, it may be necessary to develop some oxide-scale healing capability into the carbon-carbon bodies. Some of the important challenges here can be seen by recognizing that the typical approach to oxidation protection of C-C materials is via a SiC coating. The significantly higher thermal expansion and much higher elastic modulus of SiC in comparison with the carbon-carbon can result in very serious stress problems in these coatings. The Young's modulus difference will be especially critical with rotating components or any other components having significant mechanical stress as opposed to just thermal stress. Other coatings such as those based on SiO_2 may be more compatible but have been much less developed and are of greater uncertainty. Again, however, it should be noted that important developments in polymer chemistry by one U.S. firm (related to the development of ceramic fibers and composites discussed above) may also have important impact on coating possibilities for carbon-carbon material.

VI. RELIABILITY ISSUES

Significant advances have been made in flaw determination by both proof testing and nondestructive evaluation techniques and these in turn have led to significant advances in life predictions. However, much yet remains to be done. Duplication of service stresses required by present proof testing concepts has only been successfully done for turbine blades. Adequate proof tests have not been developed and are seen as challenging problems for most other components. NDE has made significant advances at the laboratory level of flaw detection. However, real world application of this is still a sustantial distance off. The ability to detect flaws has greatly advanced, but more so for isolated flaws, i.e. discrimination of critical flaws from a background of noncritical defects or flaws or with coarser surface finishes is less advanced, and detection of diffuse flaws, i.e. collection of defects such as voids that together make a critical flaw, is very uncertain. Equally critical is that,even if flaws are identified, we cannot always determine their severity, i.e. what they quantitatively mean in terms of failure stress. Further, most NDE has been on simple objects, not on complex geometries of real components. Thus, useful probabilities of false accept and false reject criteria cannot be set. Further, NDE and proof testing cannot allow for time/environmental changes of material behavior due to either changes in flaw populations or material properties and both may be less applicable to ceramic composites. This is not to say that NDE and proof testing are hopeless. As noted earlier, spin proof testing of blades (and rotors) is functional. NDE can screen out many bad components, and may have important process utility as discussed below. The key point is that NDE and proof testing are presently and will continue for some time not to be means of quantitatively determining reliability within useful probability limits for most key components on a production basis. These techniques are much more useful in demonstration programs.

However, it is felt essential to recognize that reliability of heat engines and other high technology areas has typically rested more on the interaction between process control, detailed engineering evaluation, and design iteration. This approach should also be successful with ceramics and deserves far more attention than it has heretofore had. The importance of design iteration has been briefly discussed earlier and is here again only reasserted. The focus here is on the critical role that processing plays in reliability. Although it is basically a truism, it often seems to be forgotten that even with the best NDE or proof testing capability, practical reliability will not be achieved unless the processing capabilities are adequate, i.e. either the reject rate will be too high and/or resultant cost would be exorbitant from such reject rates. In short, if you can't make it right in the first place, you won't make it right by any subsequent evaluation.

Two important aspects of processing capability and reliability should be noted. First, as discussed in the previous section, significant improvements in reliability can be feasible in manufacturing as opposed to a laboratory or pilot situation due to the dedication and specialization of people, and especially facilities. Secondly is the importance of the in-process approach to NDE that has, for example, been encouraged by some members of the Air Force. The typical approach to NDE appears to have been an end-product evaluation approach as sketched in Fig. 3A; i.e. where a component is produced and then is inspected to determine whether it is accepted or rejected. The in-process, i.e. real time, approach is to use many of the advances that have occurred in NDE capability to significantly expand the quality control inspection of the components at as many of the stages of their processing as possible or necessary as sketched in Fig. 3B. Note that the qualitative nature of much of the present NDE is much less limiting in this correlation approach. These two approaches of Fig. 3 are, of course, not mutually exclusive since a final accept or reject evaluation can be done with the in-process NDE approach. However, the in-process approach can significantly improve reliability based upon correlation of the inspection results at various stages of processing with performance. It seems that, in fact, for most systems today, including metals, the in-process approach has been the typical one used, e.g. the lack of quantitative correlation of defect character with failure stress is a problem for further fracture mechanics development and not unique to ceramics.

Finally, one other observation on end product NDE should be noted. Current NDE efforts have focused on specific quantitative defect determination for component acceptance or rejection. This is scientifically the most satisfying, useful, and sophisticated approach. However, in addition to the limits of this quantitative approach noted earlier, it is also likely to be more costly. An analog of the process correlation approach may be applicable in a number of useful cases and appears to merit more attention than it has received. The real goal of NDE as product assurance is to identify unacceptable components, not necessarily the specifics of why they are unacceptable, though this is clearly useful for process feedback. An alternate NDE approach is to find a correlation of component response to a stimulus such as vibration or radiation (e.g. IR) that, based on component tests, correlates with component success or failure. While such an approach is potentially much more component specific, and hence uncertain, there is some suggestion of this approach in earlier NDE work on ceramics at TRW. Such an approach could, for example, be investigated on a limited basis in the component manufacturing design interaction component failure test programs suggested.

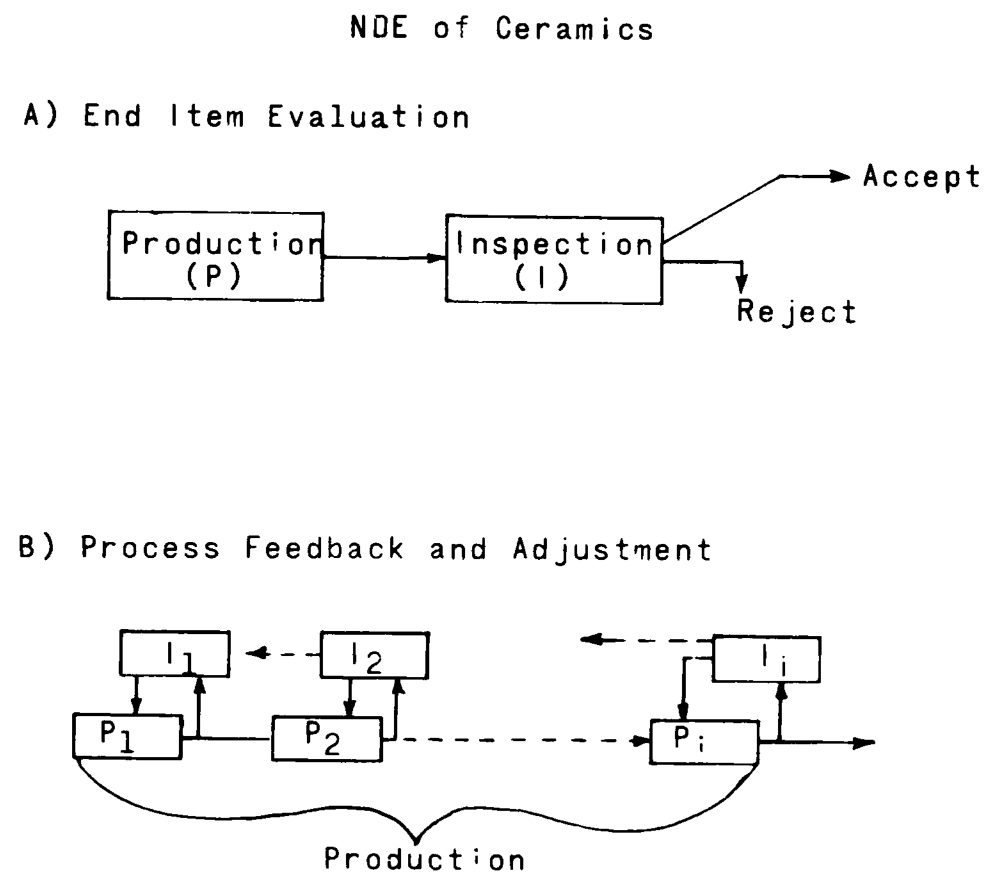


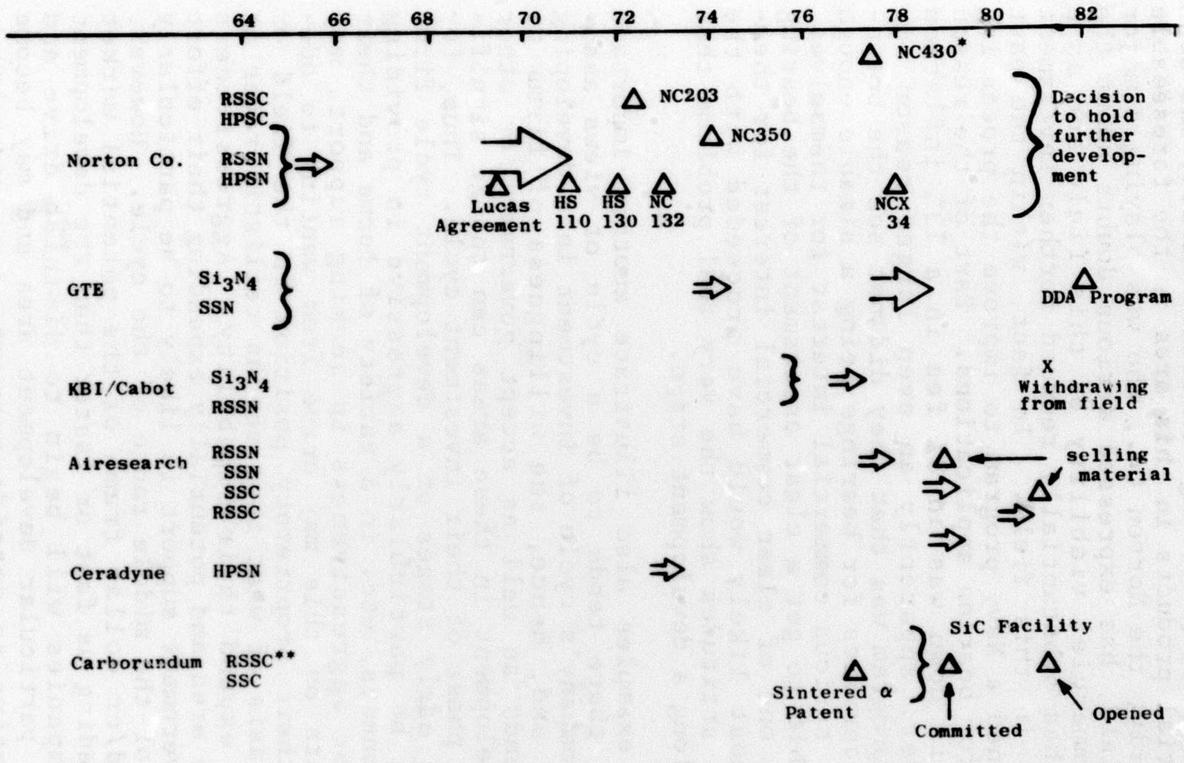
Figure 3. Approaches to NDE. A) Shows the end item approach, i.e. where a part is produced, then inspected for acceptance or rejection. B) Shows the approach of characterizing materials at many stages of the manufacturing process. Many of these would be normal quality control steps, e.g. raw material characterization. However, some of these should also make use of NDE techniques on bodies at various stages (e.g. green state) of processing. Approaches A) and B) are not mutually exclusive; they are readily used in combination.

VII. ECONOMIC AND MANAGEMENT ISSUES

Successful application of ceramic components to heat engines involves at least two basic economic considerations. First, the components have to be manufacturable at reasonable cost and second, the market has to be suitably attractive to those firms interested and capable of producing the ceramic components. Actual component costs are a difficult issue to access for two reasons. First, in many cases, ceramic component costs may not have to be as low as those of metal components if they provide significantly better engine performance. Thus, for example, since some engines are sold by horsepower, use of ceramic components would significantly increase the horsepower of a given engine over its metal counterpart, so such engines could sustain increase component cost per engine in proportion to the increase in horsepower and still be sold at the same dollar per horsepower as a metal engine. Further, with increasing fuel costs, more fuel efficient engines could economically stand a higher initial cost. Also,in the case of the adiabatic diesel, elimination of the water cooling system reduces initial costs and removes the source of about 50% of all maintenance and reliability problems. However, a central uncertainty in the potential cost of ceramic components is the fact that we do not have actual manufacturing experience on these classes of materials for anything similar to these types of applications, even in terms of shape, let alone property requirements. Further, present ceramic component costs are high and projections do not always come down to "guesstimated" desired levels, e. g. $50 per vane or blade (Table 3). However, costs should come down to desired levels with evolution of manufacturing experience and competition. This is again another reason for stressing earlier emphasis on manufacturing.

Even if ceramic components can be produced at costs that will allow the price of the resultant heat engines in which they used to be economically competitive, this alone will not assure their production. Companies must see a market that is both of suitable size and that is achievable within an acceptable time and dollar frame in order to cause them to undertake and sustain the development necessary to enter the market. The author feels that these economic considerations are very critical to this field and have not necessarily been fully realized.

Fig. 4 summarizes the authors rough assessment of the involvement of U. S. ceramic suppliers in this field. Thus, note that KBI/Cabot who could have been an important supplier of both raw materials and finished components has



*Appears to have commercial market in nonheat engine applications.

**KT SiC Patent, 1955.

Figure 4. Ceramic Supplier History. Small arrows indicate approximate initiation point, larger arrows major program expansion, and milestones. Note KBI/Cabot is withdrawing from field and Norton is holding any further effort on all but their NC-430 (for which there appears to be other sustaining markets). Also, the withdrawal of Norton's NC-134 from the market in 1978 is not shown.

withdrawn from the field. Some firms are expected to fail or withdraw for various reasons. However, the KBI withdrawal is apparently based upon the uncertainties they saw in entering a new field combined with their assessment that no viable, i.e. profit producing commercial market, was seen for their potential products in this area in the foreseeable future. Similarly, the Norton Co., who was playing a major role in this field, has expressed serious doubts about the foreseeable commercial viability of this field and as a result of this has substantially reduced further investment for development in this field. In fact, within the past year they declined a Navy program to improve the processing of their NC132 for bearing applications. Part of the reason for turning this down was an 8% fee in a 13% inflation period. However, apparently an even larger reason for declining this program was that they did not see the potential market of ceramics for bearings being a sizable enough market to be of serious commercial interest for themselves. Had they been able to get a clear assessment of the bearing market as being one of clear commercial interest for themselves, they most likely would have proceeded with the program. These attitudes show the very real problems that exist with too long a development stage.

The above examples also illustrate another important factor; namely, there tends to be a cycle of views associated with a company's cycle of investment in a developing area. The view and, hence, the willingness of firms to invest their funds as well as accept government or other support for development in these areas can change significantly with the phase of their investment cycle. Thus, for example, in the early stages of a development cycle firms may or may not be particularly aggressive in providing materials, components, etc. in a variety of forms and their receptiveness or aggressiveness in seeking support, may vary. Restraints on this may arise from wanting to adequately cover their proprietory position in the field or simply on the basis of what they see as realistic rates at which they can expand their capability. Aggressiveness in promoting the area and potentially expanding their effort by obtaining government support is likely to be particularly high over much of the middle range of the cycle. However, if the time and/or dollar frame of the potential market seems to be receding as fast or faster than the development progresses, companies will begin to diminish drive and support for the particular development area and may become much less receptive to outside support, i.e. entering a phase in which they are reassessing involvement or laying the ground work for termination of the program, if realistic markets are not seen in an adequate time frame. This appears to be precisely the position of Norton and could well become the position of other U. S. firms if potential production is not seen, e.g. by about the mid 80's.

Another important economic factor to be viewed from a national standpoint is the very heavy competition that the U.S. faces in this field from Europe, particularly West Germany, and especially from Japan. Thus, for example, note that in the Cummins program one of the two successful sources of piston caps has been Toshiba and the only source of hot pressed silicon nitride cylinder liners was Toshiba. Further, Cummins has found other Japanese organizations, such as NGK, extremely aggressive in supplying experimental components and in fact some of these have been supplied free of cost. Personnel associated with some of the major ceramic turbine programs have also noted the high level of aggressiveness and willingness of foreign firms to provide experimental components. There are typically a variety of factors that bear on this, including: 1) the current economic situation in the U. S., i.e. high inflation and economic uncertainty; 2) less incentive for longer term investment and risks in the U. S., and 3) the above cycle, i.e. many U. S. firms have been involved in this area for a longer time then many overseas competitors.

With regard to Japanese competition, Kyoto Ceramics is worthy of note in addition to NGK and Toshiba. Kyoto Ceramics has had a spectacular growth from practically a pottery shop operation about 20 years ago to a major force in the world market of high technology ceramics. For example, they apparently control about 50% or more of the world ceramic substrate market, and now own several electronics and ceramic companies in the U. S. (including Ceradyne) besides their U. S. subsidiary, Kyocera. They are now producing several forms of Si_3N_4 and SiC and are developing a variety of markets for these. Thus, for example, they apparently make several thousand Si_3N_4 guides for fishing rods per month to give them a production base to work from and apparently sintered SiC is being considered for seal rings, e.g. in air conditioners. While these applications do not necessarily demand much in terms of mechanical properties, especially at high temperatures, markets for more demanding applications, e.g. precombustion cups, are being pursued. They have four small one cylinder engines extensively testing material-design parameters for piston caps and other piston engine components. The situation in ceramics for heat engines has many similarities to that of electronics, especially of very large scale integrated circuits* and has similar, possibly even more serious, economic implications. However, the ceramic firms generally have an important difference from the electronics firms; namely that the technology of their past primary markets is much less demanding than the corresponding technology of the electronics firms.

Several management issues should also be noted. The most significant of these is how to better support U.S. industry, especially in establishing the manufacturing capability needed. Also very significant are the issues of how to get the cross-organizational support for the level of manufacturing and material R&D seen needed, as well as better trade-offs between ceramic coatings and monolithic ceramics. Better integration of various R&D programs with one another and with industry is also important. A better balance of R&D to industry is needed, and more coupling of university and industry could help in this regard. The Intertgovernmental Coordination Committee on Ceramics for Heat Engines has clearly helped. However, larger integrated material R&D programs should be seriously considered. Cooperative R&D support of promising new ideas by several funding groups should be explored to better minimize over-funding of such areas.

More generally, what appears needed are two broad governmental steps. The first is a thorough economic analysis of the <u>impact</u> and <u>cost</u> of various stages of ceramic utilization in heat engines. It is expected that the costs of implementing the extensive ceramic applications being considered is much larger than most have a sumed. However, the payoffs appear very large. If, as expected, the payoffs are on the scale generally assumed, then the second step would be to establish such ceramic utilization as a national goal both for the impact on our energy requirements and the impact on our engine and directly related, e.g. auto, industries. Designation of a national program should allow a more realistic development schedule and significantly aid in inter- and intra-agency coordination. It should be noted that a ceramic manufacturing program, e.g. patterned after the Synfuels program, could be a means of accomplishing this. Such an approach might avoid apparent limitations of DoE in aiding automotive piston-engine development, e.g. by developing the materials/manufacturing technology necessary for extensive improvement of piston engines through extensive use of ceramics.

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*For example, see discussion in <u>Time</u>, May 26, 1980, p. 45, and <u>C & E News</u>, May 26, 1980, p. 21.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1) Static components were the cause of engine failures in the ARPA/Navy/Garrett Program.

The primary conclusions regarding the engine failures in the ARPA/Navy/Garrett program are two-fold. First, the highly probable cause of failure was cracking of RSSN static components. Thermal stresses, e.g. due to hot streaking, and possibly vibration, may have contributed but the primary cause of cracking and resultant failure appears to be contact stresses. Second, the ceramic bladed rotors were a success; the extent of which was left undetermined (or hidden) by the failure of the static components which, in turn, destroyed the engine including the ceramic blades.

2) Use of Ceramics in turbine engines is feasible with blades offering particular nearer term opportunities.

The general conclusions concerning ceramics in heat engines are that the need is much greater and that a range of important applications is feasible with present design capabilities and types of materials. While static component failures in the Garrett programs show important problems, they had some limited successes with these components and the fact that static components passed overstress rig tests suggest that successful static components may not require large material/design improvements. More generally, the much more extensive success of static components in the Solar and Ford programs as well as the developing vane success in the DDA (CATE) program show that static components can be developed, at least for some applications. The blade experience in the Ford and especially the Pratt and Whitney, and Garrett programs clearly show ceramic blades have been successful for the limited times involved in these tests. In a number of important cases, ceramic blades in metal disks can be used with other metallic components. In such cases, ceramic blades can provide 50% or more of the benefits of all ceramic hot section components. Further, ceramic blades are also presently the only components for which a good quality assurance method exists, i.e. spin-proof testing. Blades also see more uniform temperatures, thus indicating blades as an area for earlier exploitation.

3) Use of ceramics in piston engines is also feasible and can have benefits equal to or greater than use of ceramics in turbines.

The success of piston caps and cylinder liners in the large Cummins engine despite a limited budget and no material development attests to the feasibility of extensive ceramic usage in diesels. This is also demonstrated by the success of other components such as precombustion cups and valve lifters which attest to a wider range of less spectacular, but important, uses of ceramics in piston engines. Performance improvements at least as great as in turbines combined with possible fuel versatility and large reductions in maintenance make such use of ceramics very important.

4) Manufacturing is the key to ceramic engine applications since it determines reliability and costs.

In order to implement the successful usage of ceramics in key heat engine applications, the most central need is to improve reliability. Reducing costs, improving design and materials are also important especially to further extend the use of ceramics both in the range and severity of application. The key to both reliability and cost is manufacturing capability. NDE and proof testing of end products is developing and useful. However, real world application of these as an absolute arbiter of reliability is probably still a substantial distance off except for spin proof testing of blades. Further, composite ceramics which offer significant potential for large increases in toughness and hence reliability may be less amenable to useful NDE. These NDE observations, thus, reinforce the need for manufacturing capability.

5) Emphasis on ceramic manufacturing development, which has been the most critical deficiency in efforts to use ceramic in engines, is needed not only for technical reasons, but also to maintain U.S. supply and competitiveness.

The critical deficiency of heat engine programs to date has been the lack of parallel material development with the lack of manufacturing development being the greatest deficiency. The properties, and especially the reliability of ceramics, are particularly sensitive to manufacturing and this is likely to increase with better ceramics, e.g. ceramic composites. Further, greater reliability can often be achieved in manufacturing than in laboratory or pilot situations due to dedication and specializations of both people and equipment in manufacturing. What is needed is suitable characterization of steps in the manufacturing process to correlate with end product performance and probably NDE in an iterative fashion. This need distinguishes such development from many typical manufacturing technology programs and puts a substantial research trust to it. Emphasis on manufacturing is also very important to sustain key corporate commitment to programs and to maintain the competiveness of the United States in the presence of impressive foreign capabilities.

6) Broader ranges of engine types, components within engines, and ceramics to meet these needs should be considered both to improve the opportunity for, and the extent of, successful use of ceramics.

A number of other conclusions on technical issues should be noted. Key hot section components should continue to be the focus of work but a broader balance of applications needs to be addressed. Some less demanding components may be excellent for initiating manufacturing capabilities and provide a basis from which to develop the manufacturing capability of more demanding components. The broader balance of applications should include more work on piston engines, combined cycles and/or hybrid engines and heat recovery, and material types. Better tradeoff and/or integration of ceramic coatings with monolithic ceramics is needed in design and development. A broader range of material development is needed for nearer term piston engine application and longer term impact on other systems such as turbine hot section components. Ceramic composites are an important component of such materials work offering nearer term potential for piston engines and possibly turbochargers, and longer term potential for turbine hot section components. Carbon-carbon materials also are important possibilities but more R&D is needed, e.g. on self healing coating capability, before key hot section application under critical oxidation conditions should be considered. Applications in noncritical areas, then short life applications, should be explored.

7) Novel designs, while potentially useful, are not needed for successful use of ceramics.

Other conclusions specifically on design issues are that the use of novel designs is not necessary for successful use of ceramics and that existing design technology needs improvement. Novel designs such as use of ceramics in compression should be explored on an R&D level since they may improve ceramic utilization. However, a better understanding of compressive behavior of ceramics is needed. Improving design technology requires improvement and verification of analysis techniques. Verification requires testing to failure and design iteration.

8) Better administrative coordination, increased emphasis on basic technology versus demonstration programs, are needed. Designating ceramic uses in engines as a national program is suggested as a means of accomplishing this.

A number of important administrative conclusions should be noted, or re-emphasized, from the above technical conclusions. Large demonstration programs have been, and will continue to be, key steps to success. However, a variety of needs exist on various scales that must be addressed but which often lack the "glamour" of demonstration programs. Ceramic manufacturing, development of better ceramics, and design technology improvement are particularly important examples of this need. Better integration of funding support in these areas, particularly the materials area, is needed. The extent of the above material-design needs is beyond the scope of R&D funding but has been left lacking because a comprehensive approach could not be sold for any one demonstration program. However, there are extensive material needs that cut across application and agency needs. Establishing the thermal mechanical reliability of one or two key ceramic components, e.g. a turbine blade or a turbocharger rotor has important ramifications for not only a variety of turbine applications, but piston and heat exchanger applications as well. Both the technical and economic scope of the opportunity/need of ceramics in heat engines and the administrative benefits indicate that much of this effort needs to be designated and run as a national effort.

9) A much more cooperative industry-government relationship is needed, but industry must continue to exercise vigorious initiative in recommending and developing programs.

Government agencies and studies such as this one can help but industry must make major contributions to policy decision and must be the primary source of programs to implement the technology. A study, such as this one, can identify needs and opportunities but the concepts of how and where to implement these must come from industry.

B. Recommendations

Implementation of, or action on, the conclusions of this report depends on a variety of factors. These include funding availability, funding organization needs and priorties, and methods (i.e. how to accomplish the goal) as well as interactive effects of implied and existing programs and the input of organizations to conduct the work. Thus, recommendations must be more limited but a number can be made starting with the immediate conclusions from the Garrett program.

1) Verify and determine extent of ceramic blade success, then apply such success.

At least one program to specifically verify the indicated success of ceramic bladed rotors should be funded. If this is substantiated, then programs to further define (e.g. to extend life) and utilize the capability of such rotors need to be initiated.

2) Determine solutions to contact stress problems.

Present empirical programs on contact stresses need to be expanded for nearer term solutions while several more basic experimental and analytical R&D programs are initiated for longer term solutions. One to three R&D programs on the micromechanics of bulk compressive failure, as well as surface (i.e. contact initiated) failure during compressive loading, should be initiated to determine the design limitations of ceramics in compression. These should specifically address cyclical loading and effects of oxidation.

3) Establish substantial ceramic reliability-manufacturing-design iteration program emphasizing sintered materials probably with rotating components.

At least two substantial programs or at least one large program are recommended to better define the reliability of ceramics and design by testing components to failure and allowing design iteration. This type of program should be done in conjunction with the recommended manufacturing development for reliability. An outline of the proposed program structure is sketched in Fig. 5. Suggested candidates are blades or rotors (e.g. for turbochargers) from Si_3N_4 and SiC, preferably emphasizing sintered materials. A study is recommended to select one to four ceramic components, the mechanisms for, and possible participants in, a program to establish actual production and use of the selected ceramic components. Such selection is recommended by 1984. Such programs must involve substantial direct funding to the ceramic component manufacturers.

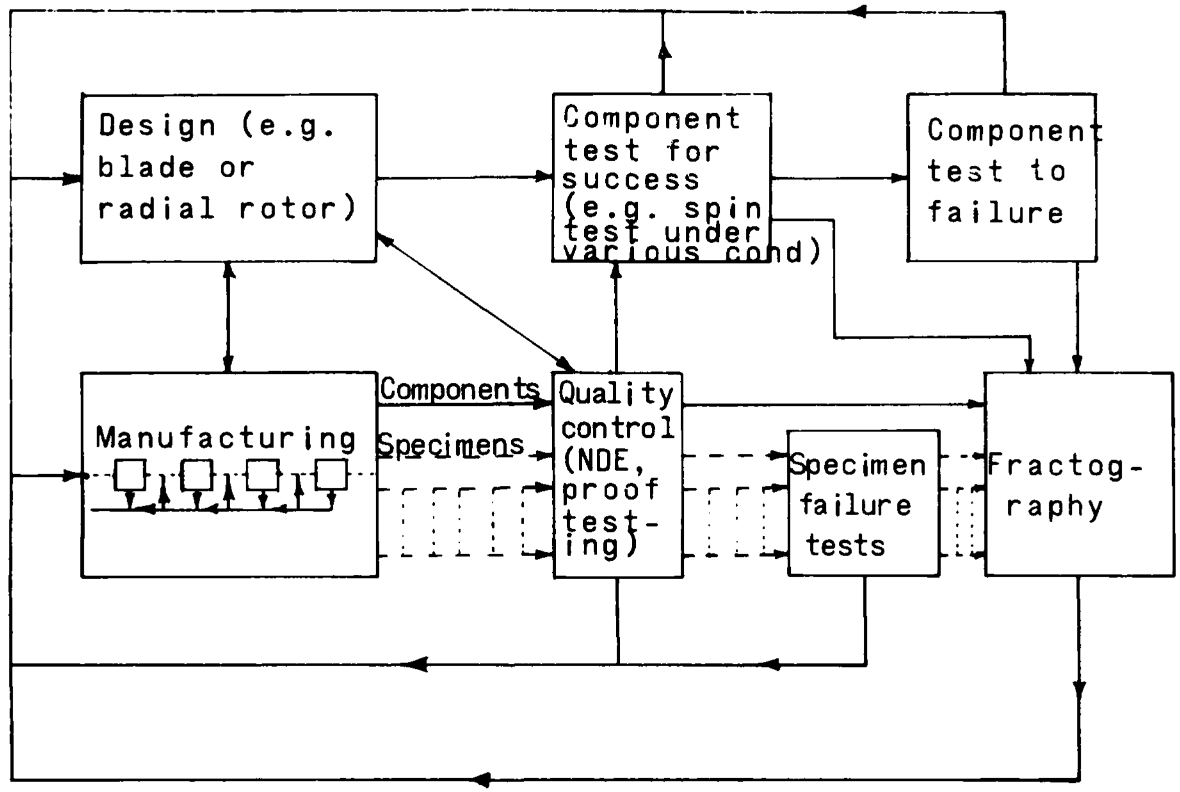

Figure 5. Suggested Ceramic Program. A comprehensive program involving manufacturing, component failure testing, and design iteration to establish reliability of key ceramic component(s), e.g. blades is shown schematically. Note the inclusion of in-process as well as end-process QC/NDE (i.e. per Fig. 3) as well as of possible parallel tests of various test specimens (dashed arrows, e.g. representing for example different size flexure bars and possibly true tension specimens). Note that most of the components of this program have existed. However, some have not, e.g. the manufacturing and component test to failure have been nearly totally absent. Other components, e.g. parallel comparison of components and test specimens have been limited. Further, the complete integration of these and true iteration has not been done.

4) Expand and diversify programs for ceramics in piston engines.

The Cummins program should be expanded and/or another program (preferably for a smaller diesel engine) be initiated with the emphasis on development and test of alternate piston and cylinder liner materials, especially ZrO_2 toughened ceramic composites and fiber composites.

5) Significant support must be given to develop truly advanced ceramic materials in addition to continued evolution of existing materials.

A major program of advanced material development is recommended. Much of this should be under one or two comprehensive programs, e.g. of 1-4 million dollars per year. Support to apply the developing polymer pyrolysis capability for fibers and possibly coating and monolithic ceramics should be part of this program as should work on CVD materials. Trial R&D efforts to investigate canless HIPing of ceramics (e. g. sintered Si_3N_4 for bearings and/or blades) should be included. Important components should be further development of ceramic composites, both particulate, and fiber composites, and their possible iteration. Manufacturing, such as shaping of glass matrix fiber composites, e.g. for turbochargers and/or diesel piston caps and cylinder liners and investigation of more refractory ceramic matrix fiber composites are important needs. R&D on non-oxide densification aids as well as on ternary compounds is also recommmended.

6) Establish mechanisms, such as a national program, for effective inter- and intra-agency support of common needs.

While full implementation of these recommendations is a large undertaking, many of the key steps could be accomplished within the confines of present and projected budgets in this area. Thus, proper scope and organization of Phase 2 of DoE's Ceramic Turbine Readiness Program, along with appropriate direction and supplementation of the DoE CATE and AGT programs could be quite useful. The DoD should continue to play an important role along with DoE. DoD-DoE collaborations are particularly important in developing the manufacturing-materials-design efforts that are needed beyond the existing programs. As noted earlier, the impact of ceramic applications on our energy usage and our transportation industries suggests that a national program, e.g. similar to the synfuels program, may be warranted. Such a program could be an improtrant component of reindustrialization by putting the auto and other key sectors of the transportation industry on an advanced, rather than existing, technology basis.